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CYCLOTRON IRRADIATION DAMAGE OF THORIUM, STAINLESS STEEL, AND ZIRCONIUM

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TABLE OF CONTENTS

ABSTRACT

The effects of cyclotron irradiation upon the hardness, the stress-strain relationship, and the electrical resistance of thorium, 347 stainless steel, and zirconium have been determined. The irradiations were carried out below -100° C on the 60-inch Crocker cyclotron. The electrical resistance measurements were made at -146° C and other measurements were made at room temperature. The results indicate that the changes in the properties due to irradiation tend to increase in magnitude up to a saturation point. The change in the thermal conductivity due to the damage has also been estimated by calculation. No changes in the metallurgical structure were noticed.

I. INTRODUCTION

Thorium, zirconium, and stainless steel are materials which are often used in reactors. As the cyclotron provides a convenient irradiation source for rapid accumulation of radiation damage, these materials were irradiated on the 60-inch cyclotron at the Crocker Laboratory of the University of California, Berkeley. The properties investigated were hardness, stress-strain relationships, and electrical conductivity.

In order to provide a basis for estimating the extent of damage which would occur at anticipated operating temperatures in a power reactor, the annealing of the radiation-induced changes was also studied. While no direct correlation between cyclotron damage and neutron damage for these materials is known at the present time, the nature of the damage in each case is similar,[1] and hence the results should be informative for estimating neutron damage.

II. HARDNESS INVESTIGATION

A. Experimental Details

In any introductory study of the effects of radiation upon metals and alloys the measurement of hardness before and after irradiation can most conveniently yield significant qualitative data. Although it is true that the absence of a change in hardness does not necessarily eliminate the possibility of changes in more subtle physical properties, the fact remains that the hardness is closely associated with the other mechanical properties.

Specimens 0.080 inch by 1.25 inches were cut from 1/16-inch sheets of each material. The zirconium was arc melted crystal bar. The thorium was cold rolled from an Ames production billet; and the 347 stainless steel was obtained from a standard commercial sheet. In order to eliminate all factors other than radiation affecting the change in hardness, all specimens were annealed to a dead soft condition. This treatment in the case of zirconium consisted of a 1-hour anneal at 750° C. The thorium was annealed for 1 hour at 700° C. It was essential that the stainless steel be investigated in a single phase condition; and to insure this, the specimens were heated to 1050° C for 1/2-hour and quenched in water. This treatment left the material in a

completely austenitic condition with no microscopic evidence for ferrite. In all cases, the heat treatments were carried out in a vacuum to minimize oxidation.

Two sets of samples, each consisting of one specimen of each of the three materials, were irradiated with 38 Mev alpha particles. In order to obtain data relating to the approach to saturation, one sample was irradiated for 40 $\mu ah/cm^2$, and the other at 80 $\mu ah/cm^2$ at a temperature below -70° C. The hardness tests were made at room temperature on a Tukon hardness tester using a 136° diamond indenter with a 1000 gram load. Impressions were made in rows of ten,perpendicular to the longitudinal axis of the specimen, and parallel to the iso-intensity axis of the beam. The readings of the ten impressions were averaged to give a hardness value corresponding to an exposure value derived from a monitoring foil mounted directly in front of the specimens. The average value of each row is located with respect to a reference mark on the specimen, and is plotted together with the beam profile in Figs. 1 through 3. From these combination beam and hardness profiles, it is possible to obtain sufficient data to plot the relation of radiation exposure to hardness. These curves, one each for thorium, stainless steel, and zirconium are given in Fig. 4.

Following the completion of the post-irradiation hardness measurements, a complete metallographic study of all specimens was carried out. Based upon previous studies of other metals, no structural changes were expected; and none were found. The low temperature of the bombardment precludes the possibility of grain growth, since it has been demonstrated that radiation alone produces no such effect. It might be expected that the passage of heavy particles would result in a reduction in grain size particularly if the Thermal Spike Theory is accepted. However, these regions which were presumed to be heated by the thermal spikes were not sufficiently large to be visible at ordinary magnifications, and the grain structure observed would appear unaltered. In the stainless steel, the possibility of a phase change exists since the austenite is thermodynamically unstable at room temperature. The work by Reynolds, Low, and Sullivan[2] indicates that the amount of transformation induced by neutron irradiation is extremely small and tends to corroborate the present findings that no microscopically observable transformation occurs.

Photomicrographs of the irradiated and non-irradiated stainless steel are presented in Fig. 5.

Since the experiment provided only a limited number of irradiated specimens of each material, it was not possible to carry out rate studies of the annealing process. However, by holding each specimen for one hour at successively higher temperatures followed by hardness determinations, it was possible to establish a minimum temperature at which annealing became significant. Since each sample had been heated to about 150° C during mounting for the metallographic examination, the annealing treatments were started at 200° C. The results are best shown by Fig. 6. In each case, the hardness numbers indicated are an average of five readings taken at the peak of the hardness profile of the most heavily damaged specimens of each material. In each series of readings, the maximum deviation was not greater than three hardness numbers.

B. Discussion of the Results

Of primary interest in the present investigation is the rate at which the materials being studied approach damage saturation, as measured by hardness. Only in the case of the stainless steel has saturation apparently been reached. Referring to Fig. 4A, it can be seen that the hardness vs exposure curve has reached its maximum value at about 50 $\mu ah/cm^2$, and undergoes no further change with increased exposure. This maximum hardness value of 260 Diamond Penetration Hardness (DPH) is essentially that which can be obtained by severe cold work. It will be noted that in the case of the other two materials, the hardness has not reached a uniform value at 80 $\mu ah/cm^2$, and consequently cannot be said to have reached an equilibrium condition. In the cyclotron experiments, the specimen temperature was -70° C or below during irradiation, and 20° C during hardness measurements. It is reasonable to expect that some of the increase in hardness produced at -70° C had been removed by annealing at the measurement temperature.

It is apparent from the annealing results obtained that, in the case of thorium and zirconium, the annealing of radiation damage, as represented by hardness changes, is essentially carried to completion in 1 hour at temperatures between 200 and 300° C. The equivalent temperature range for the stainless steel is apparently slightly higher, being between 300 and 400° C.

III. STRESS-STRAIN RELATIONSHIPS

A. Experimental Details

The specimens utilized for the stress-strain measurements were in the form of wires of 347 stainless steel, arc melted zirconium, and Ames thorium with diameters of 0.005 inch, 0.0075 inch, and 0.011 inch, respectively. The specimens were cold drawn to size from wires supplied by the California Research and Development Corporation, so that the complete prior history is unknown. However, it is reasonable to assume that a rather highly oriented material annealed to a dead soft condition was produced by the following treatments: zirconium - 1 hour at 750° C; thorium - 1 hour at 700° C; and stainless steel - 1/2 hour at 1080° C, followed by a water quench. All heat treatments were carried out in a vacuum.

The targets for the cyclotron were arranged to contain approximately 24 wire specimens, eight of each material. The specimens were 1 inch long and were placed in the target so that 1/4 inch at each end was shielded, leaving the center 1/2 inch exposed to the beam. Two such targets were prepared and subjected to approximately 40 and 80 μah/cm^2 irradiation, respectively, from 38 Mev alpha particles. The targets were oscillated in the beam to insure uniform irradiation over the length of each specimen. During both irradiations, the targets were cooled so that the specimen temperature during irradiation did not rise above about -70° C. Following the irradiation, the specimens were allowed to reach room temperature equilibrium prior to testing.

The stress-strain curves of the wire specimens were obtained on an apparatus consisting essentially of two pin vise grips, one movable. The other was fixed to a steel beam supported at each end on knife edges. This beam was previously calibrated to provide a load deflection relationship. This deflection was measured by means of a dial indicator. The movable grip was actuated by a motor-driven micrometer screw which provided a measure of the total displacement of the grip. However, more precise measurements of the initial length as well as the increments of extension were obtained with a traveling micrometer. It was not possible to obtain continuous readings of load <u>vs</u> extension. Therefore, the length measurements had to be made after each addition to the load.

The stress-strain curves for irradiated and non-irradiated specimens of each material are presented in Fig. 7. The plotted points are the average values obtained from three or four specimens of each type of material. With the exception of the thorium, the maximum deviation was not over 5 per cent. It was noted that no difference could be measured between those specimens obtained from the 40 μah/cm^2 irradiation as compared with the specimens from the higher irradiation. Either saturation is reached near 40 μah/cm^2, or the measurements are insensitive to the small changes which take place beyond that point.

It should be noted that the last point on each curve does not represent the ultimate strength, but is only the last strain reading taken prior to rupture. The true ultimate strengths, however, are not appreciably greater than the stress value indicated by the terminal points of the curves. It should also be noted that all specimens broke in the gage length, thus eliminating all concern over the effects of the grips.

B. Discussion of Results

It should be recognized at the outset that no direct comparison can be made with the data presented here and those reported in the literature. The highly oriented character of the fine wire undoubtedly emphasizes any anisotropic characteristics that the material may possess. This anisotropy is most evident in elastic moduli values. In addition, the strength and elastic properties are somewhat dependent upon sample size. For these reasons, then, it is recommended that these data be evaluated on a relative rather than an absolute basis.

Although the effects of radiation are more clear in the case of the zirconium and stainless steel, it can be stated generally that in all three materials the strength is increased. This would be expected on the basis of the earlier work on hardness. It is not possible to assign a reliable value for Young's modulus on the basis of such data, because the apparatus is insensitive to the small dimensional changes which take place within the elastic range. However, it does appear that radiation increases the value of modulus.

It is similarly apparent that the yield points of zirconium and the 347 stainless steel are increased by irradiation. The amount of this increase can be placed at approximately 30 per cent. Although the ultimate strengths

are not affected greatly, the decrease in ductility increases the strength for a given elongation by approximately 40 per cent for the zirconium and stainless steel.

No explanation can be given at present for the rather unusual stress-strain relationship exhibited by the thorium specimens. There is obviously an increase in strength and a decrease in ductility. However, the apparent changes in the slope of the initial portions of the curve are unique. This effect is emphasized in the irradiated material to the extent that this curve crosses that of the non-irradiated material twice. Although the spread in the data for thorium is greater than for the other materials, this change in slope is characteristic of all specimens tested and is not the result of averaging the data.

IV. ELECTRICAL RESISTIVITY

Materials investigated were low-hafnium crystal bar zirconium, Ames thorium, and type 347 stainless steel. The samples were prepared in the form of thin foils 10 mils, 6.7 mils, and 7 mils thick, respectively; these thicknesses are approximately one-third of the particle range. Prior to irradiation, the samples were given the following annealing treatments in a vacuum: Zirconium, 750 to 800° C for 1/2 hour; stainless steel, 1080° C for 15 minutes; and thorium, 600° C for 1/2 hour.

A. Method of Irradiation

The samples were irradiated with 19 Mev deuterons at an average current density of 1 to 2 $\mu a/cm^2$. They were maintained at temperatures below -100° C by means of a stream of cool helium gas in order to reduce the rate of thermal annealing. Measurements of resistivity were made at -146° C at frequent intervals during the irradiation.

Immediately following the irradiation, annealing studies were made on the irradiated specimens at temperatures up to 100° C in order to obtain data on the kinetics of recovery and resistivity changes. Details of the experimental techniques employed in the preparation of the samples, and in carrying out the irradiation and the property measurements have been described in earlier reports.[3,4]

B. The Effect of Irradiation

The results of the low temperature measurements of resistivity as a function of deuteron irradiation are shown in Figs. 8, 9, and 10. The temperature annealing results which are shown in Fig. 11, indicate that little annealing should be expected at the temperature of irradiation. The trend toward saturation which is evident in Figs. 8, 9, and 10 can therefore probably be ascribed to mechanisms other than thermal annealing.

The curves in Figs. 8, 9, and 10 can be empirically described by an equation of the form

$$p = a(1-e^{-b\mu})$$

where

$$p = \frac{\rho - \rho_o}{\rho_o} ;$$

μ = the exposure in μah/cm^2;

ρ is the resistivity after an exposure μ in microhm-cm; and

ρ_o is the resistivity at $\mu = 0$, both taken at -146° C.

a and b are empirical constants.

The equation was fitted to the experimental data by trial and error with the results shown by the dotted curves of Figs. 8, 9, and 10. The empirical curve was purposely fitted so that for long bombardments it yields resistivity values somewhat higher than the experimental data. The saturation value of the resistivity at -146° C, ρ_s, as derived from the above equation should then be an over-estimate. The saturation values obtained in this manner for deuteron irradiation at low temperatures, where annealing effects are essentially absent, are as follows:

zirconium $\rho_s = 1.52\ \rho_o$

thorium $\rho_s = 1.30\ \rho_o$

steel $\rho_s = 1.06\ \rho_o$

C. Saturated Resistivity at Elevated Temperatures

Similar experiments,[4] in which the effect of cyclotron bombardment on the temperature coefficient of resistivity of Zr, Al, Cu, and certain Au-Cu alloys was investigated, have shown that at low temperatures, where annealing effects are absent, the resistivity vs temperature curves of irradiated and

unirradiated metals are very nearly parallel. The absolute increase in resistivity which results from irradiation is therefore taken to be independent of temperature, if the effects of annealing are for the moment ignored. The "saturation" resistivity at elevated temperatures in this case is then easily calculated by using the temperature coefficient of resistivity as reported by Bing[5] for zirconium, and from data taken at this laboratory on the electrical resistance over a suitable range of temperature for thorium and stainless steel. The following results are then obtained for "saturation" resistivities at 300° C and 500° C, in which the effect of annealing has not been taken into account:

	Zirconium	Thorium	Steel
$\left(\frac{\rho_s}{\rho_o}\right)_{T\,=\,300°\,C}$	1.11	1.08	1.04
$\left(\frac{\rho_s}{\rho_o}\right)_{T\,=\,500°\,C}$	-	1.06	1.03

D. Effect of Annealing

Complete saturation was not attained in these samples, but it is felt that the annealing kinetics would be little changed by a closer approach to saturation. The annealing curves are shown in Fig. 11, in which the ordinate gives the resistivity of the irradiated specimens after annealing at a given temperature relative to that of the specimens in the fully annealed condition. The annealing time at each temperature was 5 minutes, and all resistivity measurements were made at -146° C.

The ratios of the resistivity, ρ, to the initial unirradiated resistivity, ρ_o, where the values of ρ are those obtained after treatment for 5 minutes at the highest annealing temperature (100° C), are as follows:

	Zirconium	Thorium	Steel
$\left(\frac{\rho}{\rho_o}\right)_{T\,=\,-146°\,C}$	1.06	1.14	1.025

The slopes of the annealing curves at 100° C indicate that the equilibrium values at higher temperatures will be even lower.

For considerations of the recrystallization temperatures of zirconium, thorium and 347 steel, and with some guidance from data[6] on the annealing kinetics of irradiated copper at higher temperatures, the following values appear to be reasonably conservative estimates of the equilibrium resistivities, ρ_e, to be expected after long irradiation at 300° C:

	Zirconium	Thorium	Steel
$\left(\frac{\rho_e}{\rho_o}\right)_{T = 300° C}$	1.01	1.03	1.01

At 500° C, the effect of annealing in zirconium and thorium is likely to be appreciably greater than at temperatures near 300° C because of the relatively low recrystallization temperatures of these metals. Consequently, since the equilibrium resistivities expected at 300° C are already low, no similar estimates were made for these materials at 500° C. However, for stainless steel the recrystallization temperature is sufficiently high that the estimate of 1.01 was made for $(\rho_e/\rho_o)_T$ at an operating temperature of 500° C.

V. ESTIMATES OF THERMAL CONDUCTIVITY CHANGES

A. Zirconium

Bing[5] has reported the following empirical relation between thermal and electrical conductivity to be valid for zirconium and several zirconium alloys over the temperature range 0° to 300° C:

$$K = 0.0308\,(\sigma - 0.00327)\,T + 0.0381$$

where:

K is the thermal conductivity in watt-cm^{-1}-°C^{-1}

σ is the electrical conductivity in (microhm-cm)$^{-1}$

T is the absolute temperature in degrees Kelvin.

Since this relation holds when alloying elements are added to zirconium, it is reasonable to assume that it will also apply to irradiated material. The thermal conductivities corresponding to irradiated and unirradiated electrical resistivities are then easily calculated:

$$K_o = 0.173 \text{ watts-cm}^{-1}\text{-°C}^{-1}$$
$$K_e = 0.170 \text{ watts-cm}^{-1}\text{-°C}^{-1}$$

where K_e and K_o are the equilibrium irradiated and unirradiated values respectively at 300° C.

The effect on the electrical resistivity at an operating temperature of 500° C has already been considered, and the authors have indicated that the expected equilibrium values under irradiation probably approach very closely the unirradiated values. There is no reason to believe that the corresponding thermal conductivity values would not behave similarly.

If one wishes to take the conservative viewpoint, and assume that the effects of annealing have been overestimated, then one may calculate that the "saturation" value of the thermal conductivity, which ignores completely thermal recovery of irradiation effects, as

$$K_s(\text{at } 300° \text{ C}) = 0.153 \text{ watts-cm}^{-1}\text{-°C}^{-1}.$$

B. 347 Stainless Steel

Powell[7] has reported an empirical relation between the electrical and thermal conductivity for 18-8 stainless steel.

$$K = 0.625 \times 10^{-8}\sigma T + 0.006$$

where

K is in gm-cal-sec^{-1}-cm^{-1}-°C^{-1}

σ is in (microhm-cm)$^{-1}$

T is the absolute temperature in degrees Kelvin.

He found that experimental data for 18-8 stainless steel fitted this expression within 12 per cent. Annealed values of the thermal conductivity were obtained from the Metals Handbook,[8] and these, together with the ρ_e/ρ_o values already given (section IV-D), allowed a calculation to be made of the equilibrium thermal conductivities, K_o and K_e:

at 300° C, $K_o = 0.191$ watts-cm^{-1}-°C^{-1}

$K_e = 0.189$ watts-cm^{-1}-°C^{-1}

and at 500° C, $K_o = 0.221$ watts-cm^{-1}-°C^{-1}

$K_e = 0.219$ watts-cm^{-1}-°C^{-1}.

The conservative values, with no back annealing considered, are:

at 300° C, $K_s = 0.185$ watts-cm^{-1}-°C^{-1}

500° C, $K_s = 0.215$ watts-cm^{-1}-°C^{-1}

C. Thorium

Unfortunately, there are no extensive data available connecting the thermal and electrical conductivity of thorium. In this case, in order to calculate a thermal conductivity under irradiation at the elevated temperatures, it can be assumed that the experimental Wiedemann-Franz ratio at any one temperature is not changed by irradiation.

The irradiated thermal conductivity at 300° C was calculated from $K_e - K_o\ \rho_e/\rho_o$, where K_o was obtained from data by Marsh,[9] and ρ_e/ρ_o has been determined in section IV-D to be 1.03. Then at 300° C

$$K_o = 0.402 \text{ watts-cm}^{-1}\text{-°C}^{-1}$$
$$K_e = 0.391 \text{ watts-cm}^{-1}\text{-°C}^{-1}$$

The equilibrium change in thermal conductivity at 500° C would be expected to be even smaller.

If a very conservative view is taken, and the effects of thermal annealing are ignored completely, one obtains the "saturation" values:

K_s (at 300° C) = 0.372 watts-cm^{-1}-°C^{-1}

K_s (at 500° C) = 0.406 watts-cm^{-1}-°C^{-1}

Examination of the empirical relations given by Bing and Powell for zirconium and steel, respectively, shows that they are essentially based on the assumption of a constant Wiedemann-Franz ratio, to which correction terms have been added. Table I compares the results obtained when a constant experimental Wiedemann-Franz ratio is assumed with the previous results obtained (in section V-A and B) using the empirical relations for zirconium and 347 stainless steel. The difference in every case is less than 2 per cent. This suggests that the results for thorium are not significantly in error due to the assumption of a constant Wiedemann-Franz ratio. It should be borne in mind that the deuteron irradiation produced very little fissioning in the case of thorium, and these results do not provide a basis for estimating the effect of the presence of fission products on the thermal conductivity.

TABLE I

THERMAL CONDUCTIVITY FOR ZIRCONIUM AND 347 STAINLESS STEEL

	Zr		347 Stainless Steel	
	Wiedemann-Franz Ratio	Bing's Empirical Relations	Wiedemann-Franz Ratio	Powell's Empirical Relations
K_e (at 300° C)	0.171	0.170	0.183	0.189
K_e (at 500° C)	-	-	0.219	0.219
K_s (at 300° C)	0.156	0.153	0.184	0.185
K_s (at 500° C)	-	-	0.214	0.215

VI. SUMMARY

Results of this investigation indicate an apparent saturation in the electrical resistivity of zirconium, thorium and 347 stainless steel with increased deuteron irradiation. At temperatures where the annealing effects are small, this saturation value is appreciably greater than the annealed unirradiated value. The largest increase is found for zirconium. In this case, the saturation value is 1.52 times greater than the unirradiated value. It is further shown that a major portion of this radiation-induced resistivity is removed by annealing to 100° C. These results, together with the estimates of equilibrium electrical resistivity at higher temperatures, are summarized in Table II. The corresponding estimated changes in thermal conductivity are summarized in Table III.

An equivalent tendency toward saturation is noted in the radiation effects on the hardness, and to a less distinct extent on the yield point and ultimate strengths of these materials. The maximum changes in these mechanical properties are altered to the least extent.

In contrast to the annealing characteristics of the radiation-induced electrical resistivity change, the hardness remains essentially unaltered on annealing to approximately 200° C in the case of zirconium and thorium, and to approximately 300° C in the stainless steel. One hour at these temperatures removes approximately 95 per cent of the hardness change. It was not possible

to measure the annealing effect on the stress-strain relationship. However, it is not unreasonable to anticipate a close correlation with the results obtained in the hardness study.

TABLE II

RESISTIVITY RATIOS OF IRRADIATED METALS BEFORE AND AFTER ANNEALING AT SEVERAL TEMPERATURES

		Zirconium	Thorium	Steel
Irradiated Saturation Value without Subsequent Annealing				
$\left(\frac{\rho_s}{\rho_o}\right)_T$	Measured at T = -146° C	1.52	1.30	1.06
	Referred to T = 300° C	1.11	1.08	1.04
	Referred to T = 500° C	-	1.06	1.03
Resistivity after Irradiation and Annealing to +100° C				
$\left(\frac{\rho}{\rho_o}\right)_T$	Measured at T = -146° C	1.06	1.1[illegible]	1.025
Resistivity after Irradiation and Annealing to +300° C (estimated)				
$\left(\frac{\rho_e}{\rho_o}\right)_T$	T = -146° C	1.05	1.10	1.02
	T = 300° C	1.01	1.03	1.01
Resistivity after Irradiation and Annealing to +500° C (estimated)				
$\left(\frac{\rho_e}{\rho_o}\right)_T$	T = -146° C	-	-	1.02
	T = 500° C	-	-	1.01

where: ρ_s = saturation resistivity in microhm-cm.

ρ_e = equilibrium resistivity under irradiation and temperature T.

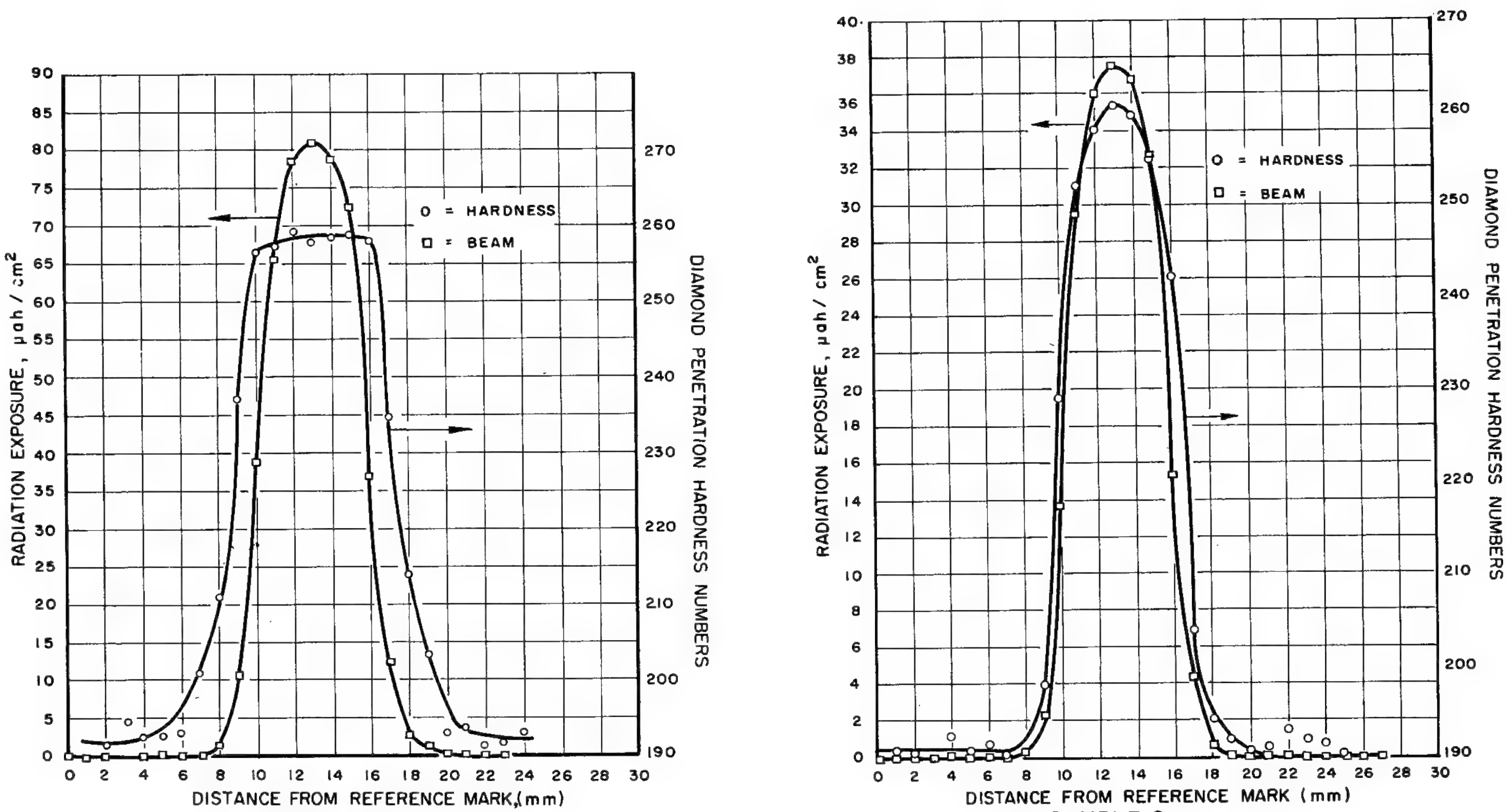
ρ_o = unirradiated resistivity.

TABLE III

COMPUTED THERMAL CONDUCTIVITY*

	Zirconium	Thorium	347 Stainless Steel
	Bing's Empirical Relations	Wiedemann-Franz Ratio	Powell's Empirical Relations
Unirradiated:			
300° C	0.173	0.402	0.191
500° C	--	0.431	0.221
Equilibrium value for Irradiation at:			
300° C	0.170	0.391	0.189
500° C	--	--	0.219
Irradiated Saturation value assuming no back annealing:			
300° C	0.153	0.372	0.185
500° C	--	0.406	0.215

*Values given are thermal conductivity in units of watts-cm^{-1}-°C^{-1}.



A. SAMPLE 1.   B. SAMPLE 2.

Fig. 1. Beam and Hardness Profiles from 347 Stainless Steel

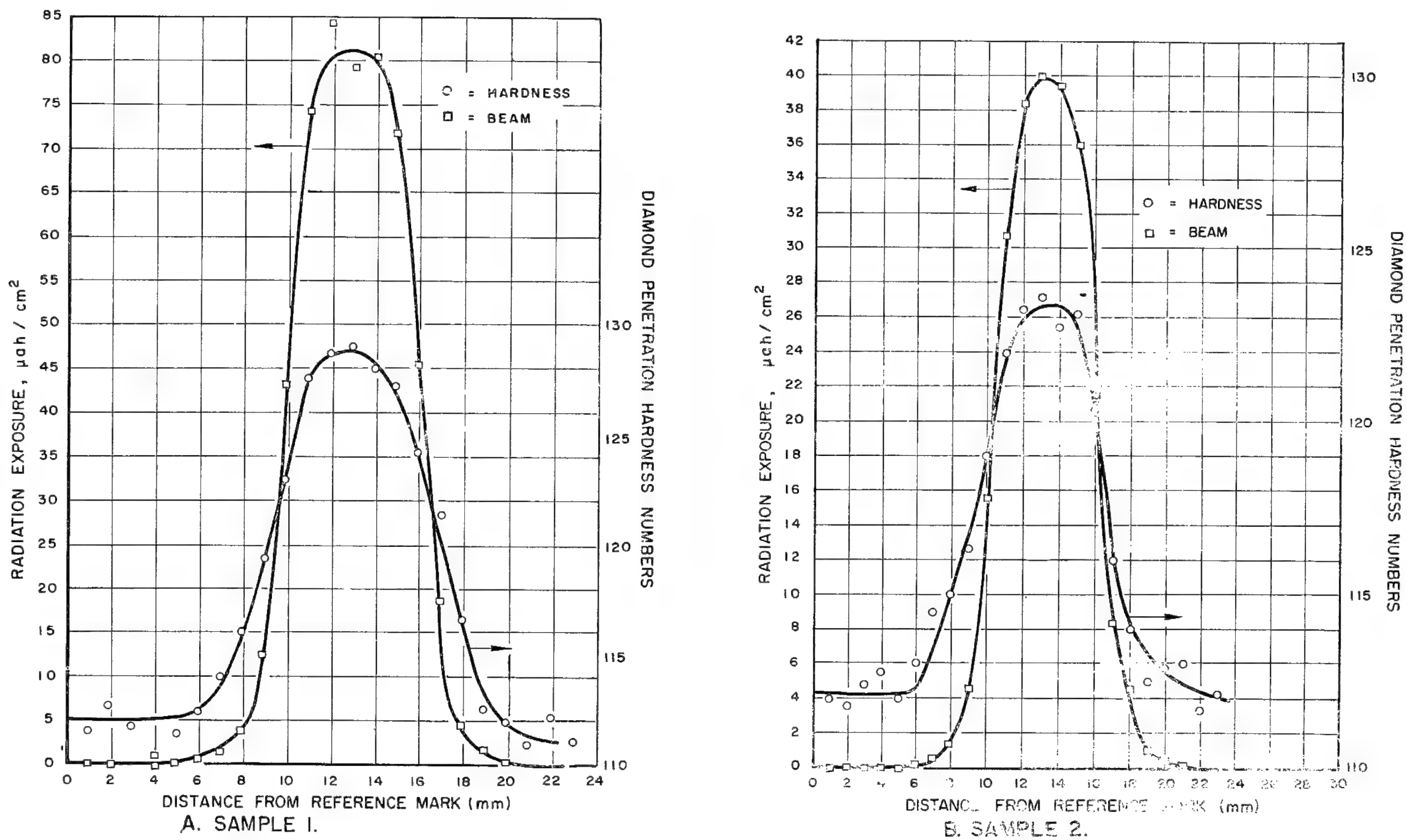


Fig. 2. Beam and Hardness Profiles from Thorium

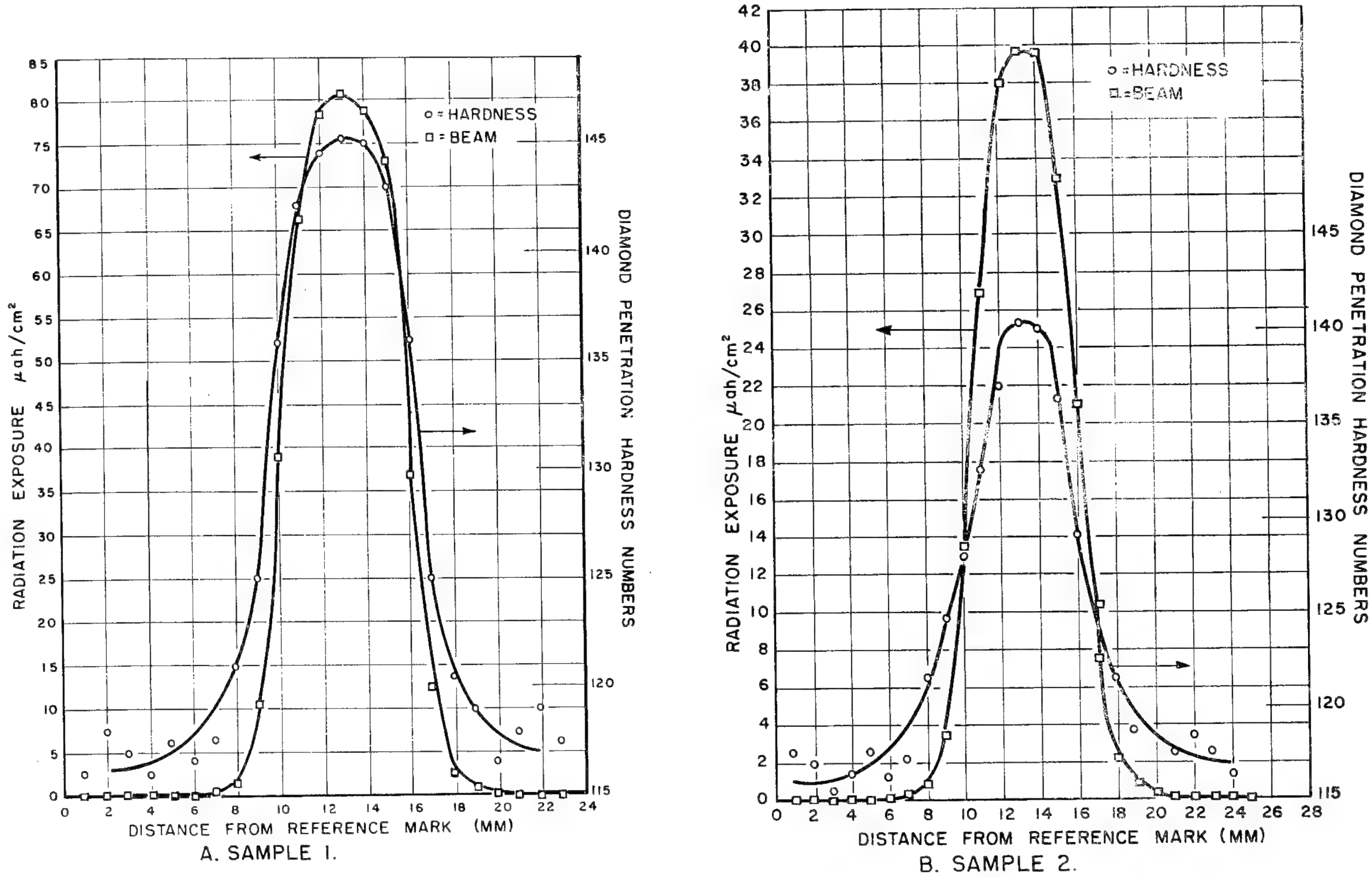


Fig. 3. Beam and Hardness Profiles from Zirconium

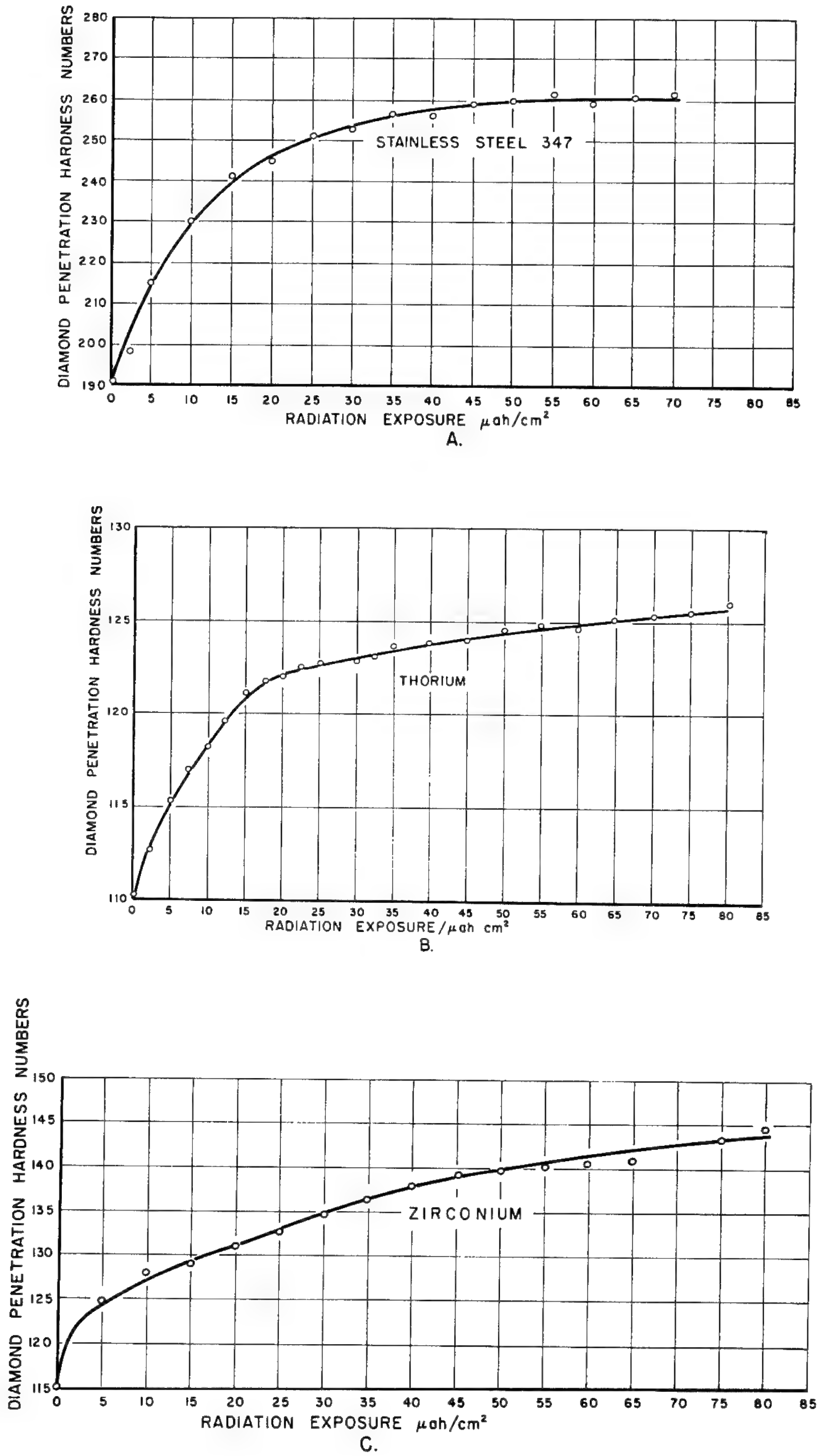
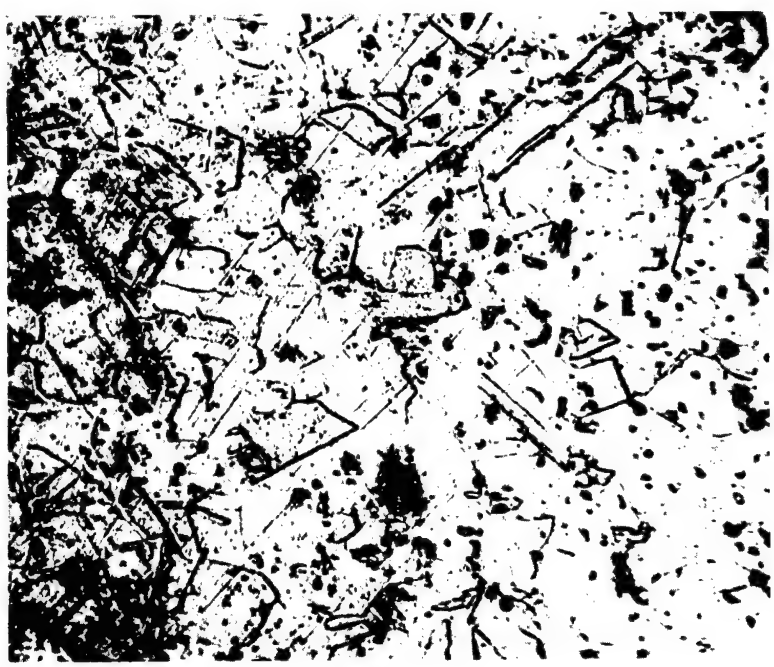


Fig. 4. Radiation Damage Saturation Curves

GPO 822892 - 2

Nonirradiated 347 Stainless Steel 500x
Electrolytic Oxalic Acid Etch



Irradiated 347 Stainless Steel 500x
Electrolytic Oxalic Acid Etch 80 amp hrs/cm^2 of 39.6 Mev Alphas

Fig. 5. Structural Effects of Radiation on 347 Stainless Steel

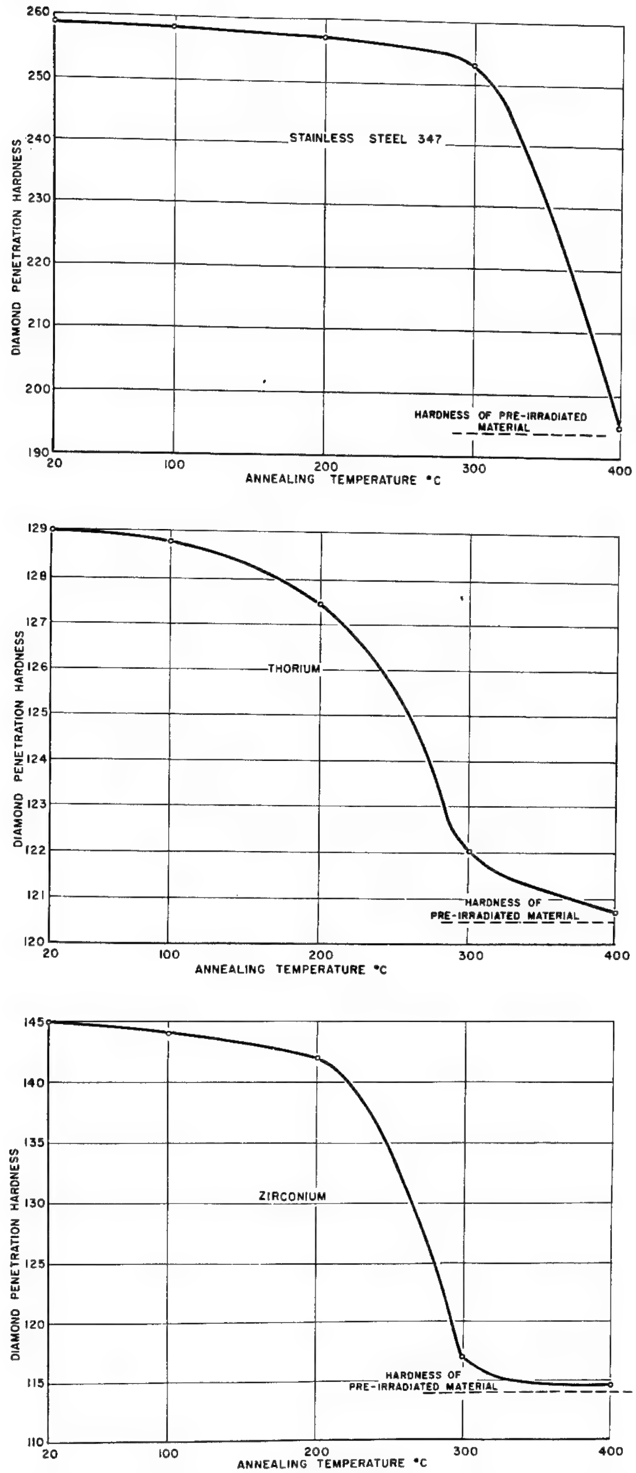


Fig. 6. Annealing Radiation Damage in Irradiated Materials (One hour at each temperature)

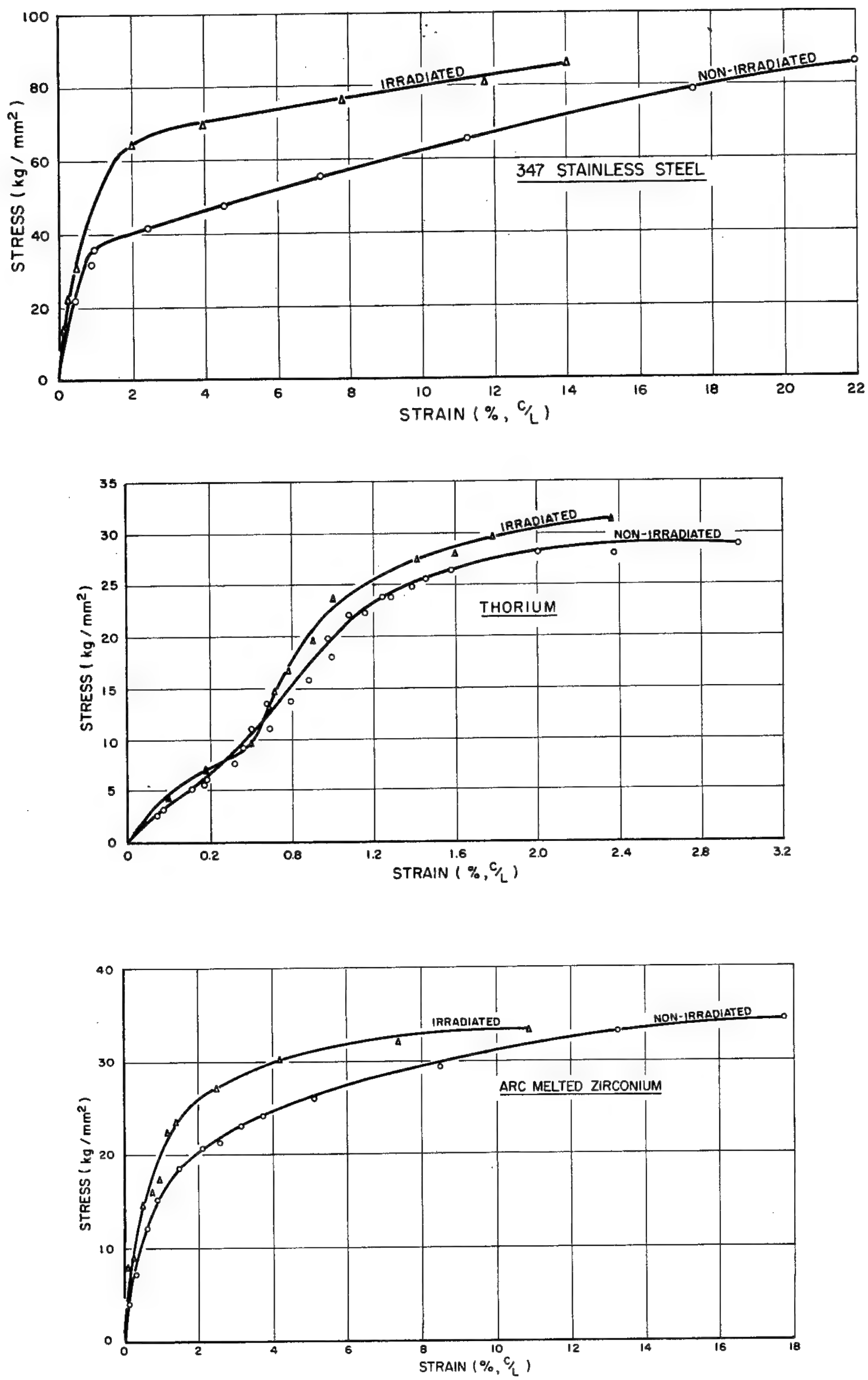


Fig. 7. Stress Strain Curves for Irradiated and Nonirradiated Materials

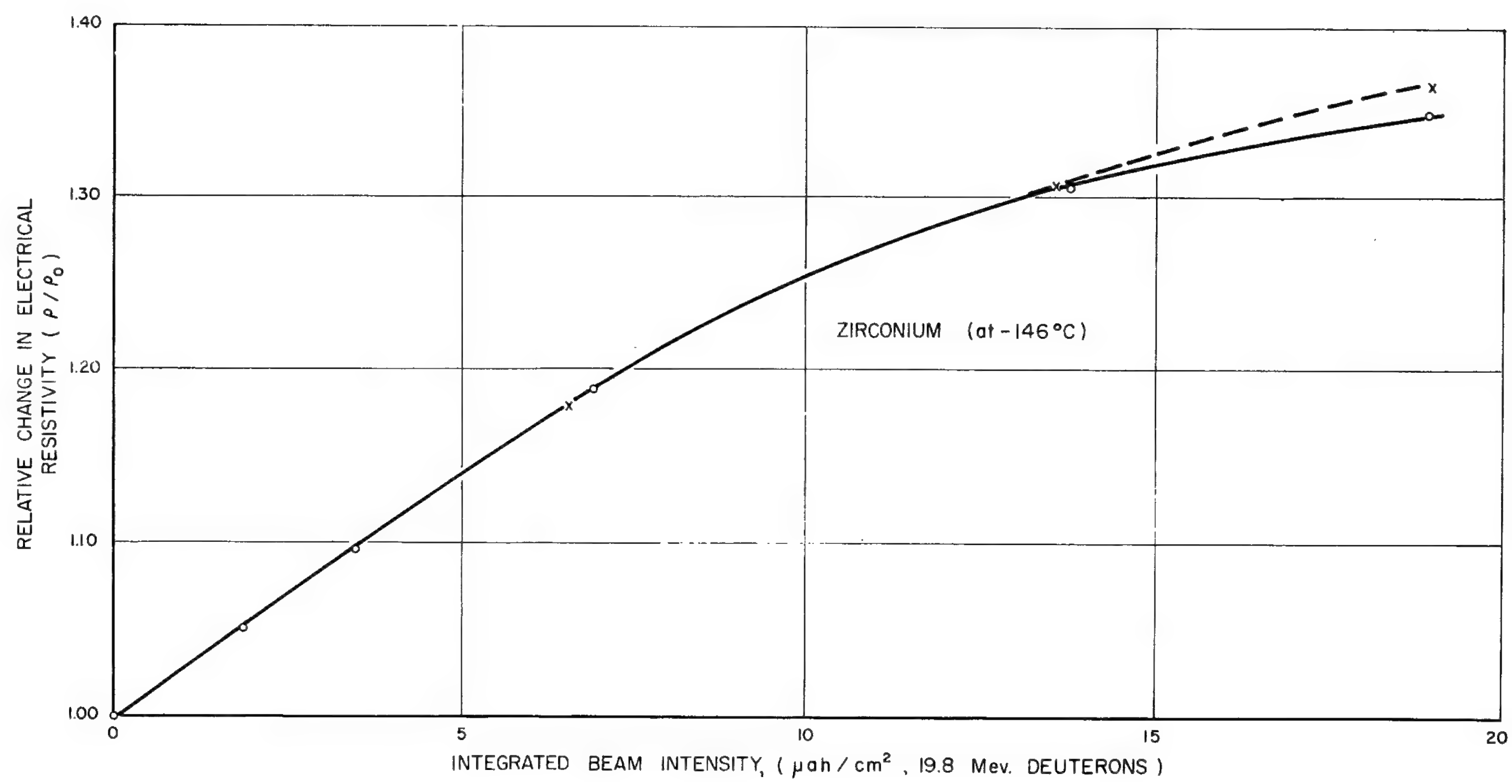


Fig. 8. Relative Change in Electrical Resistivity of Zirconium (at -146° C) vs Integrated Deuteron Beam Intensity

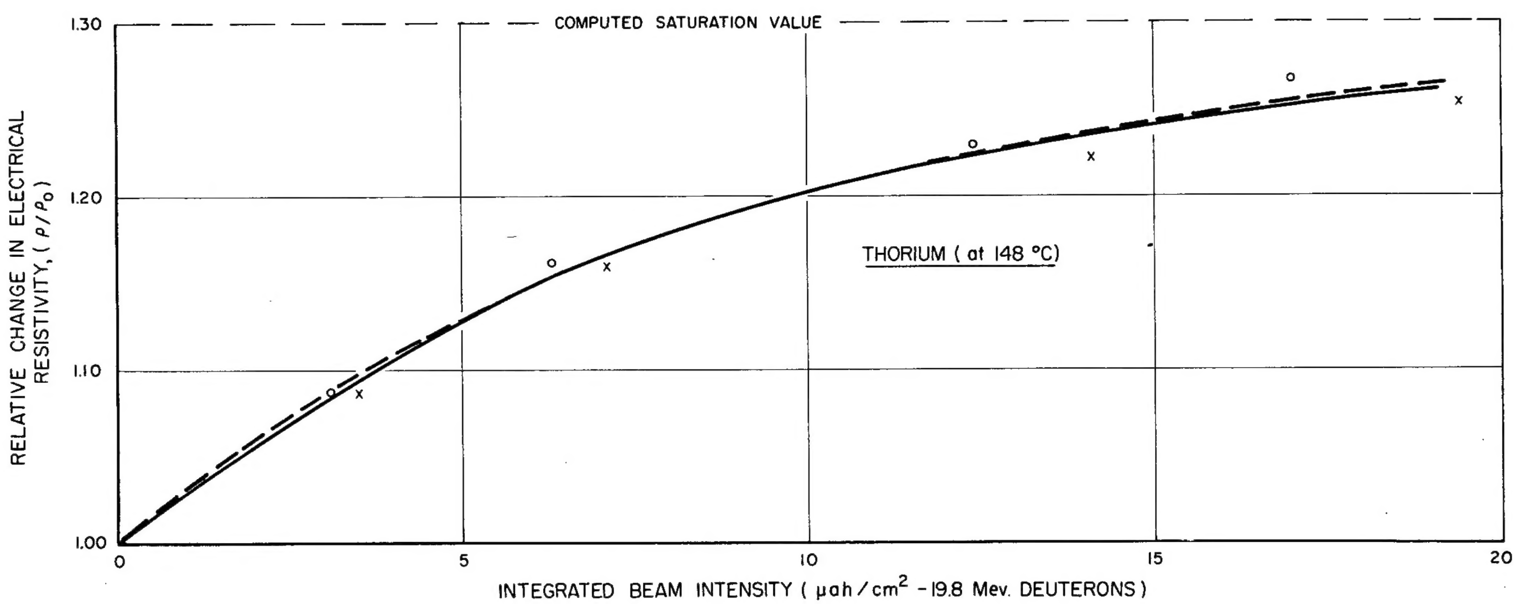


Fig. 9. Relative Change in Electrical Resistivity of Thorium (at -148° C) vs Integrated Deuteron Beam Intensity

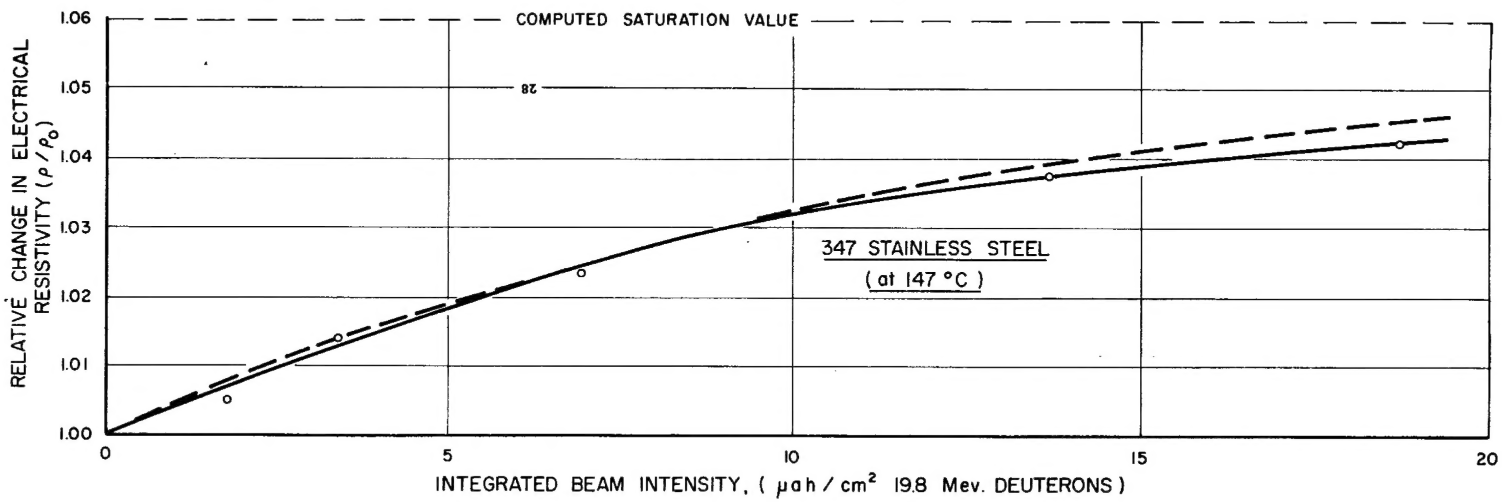


Fig. 10. Relative Change in Electrical Resistivity of 347 Stainless Steel (at -147° C) vs Integrated Deuteron Beam Intensity

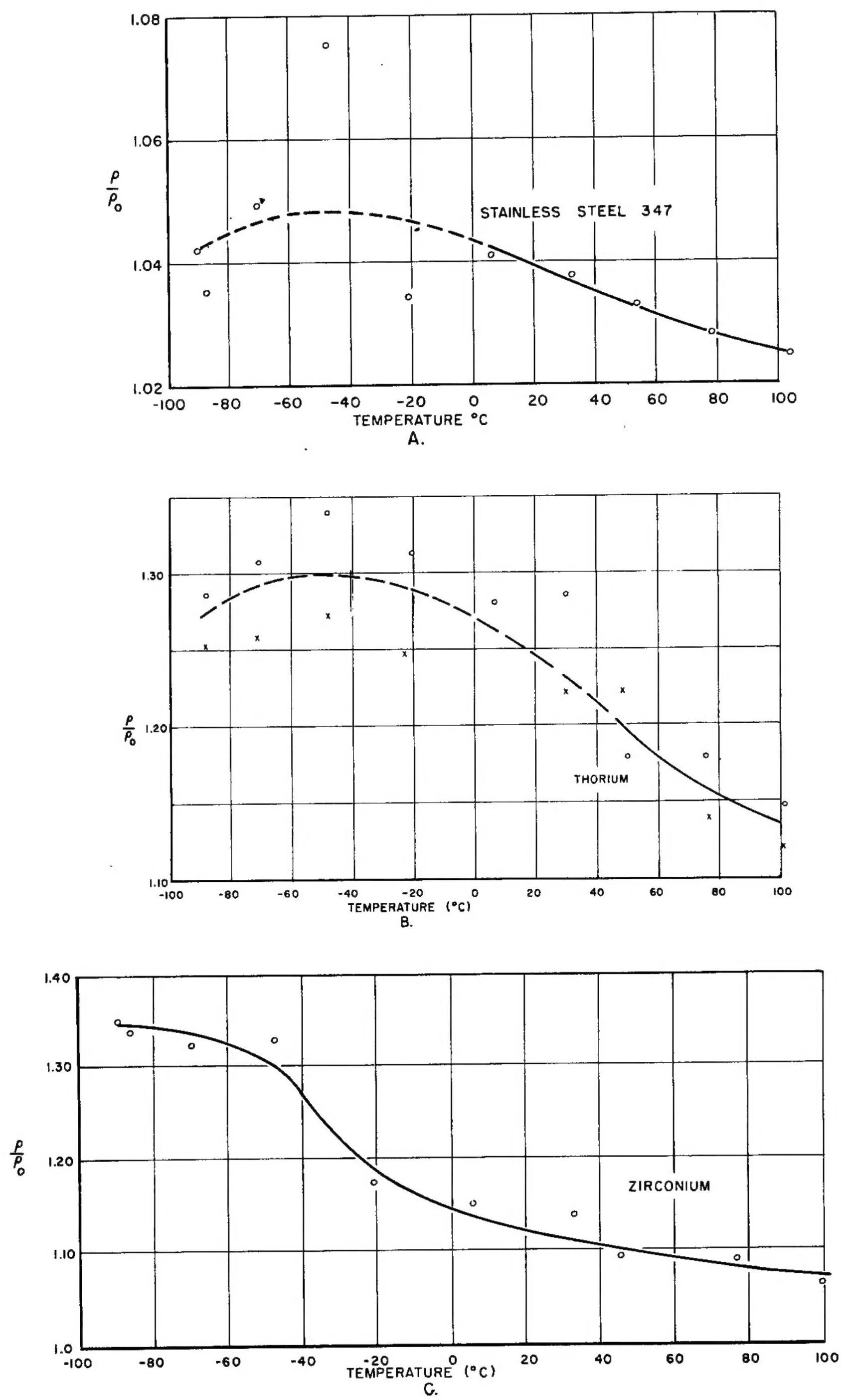


Fig. 11. Relative Change in Electrical Resistivity of Bombarded Materials $\left(\frac{\rho}{\rho_0}\right)$ vs Temperature of Five Minute Annealing Pulse

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GPO 822892 - 1